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3D MEMS Air-core Inductor in a Very High Frequency Switched-Mode Power Converter

Hoa Thanh Le^{a,b}, Yasser Nour^b, Ziwei Ouyang^b, Arnold Knott^b, Flemming Jensen^a, Anpan Han^a

^a National Center for Micro and Nanofabrication (DTU Danchip), ^b DTU Electrical Engineering (DTU Elektro), Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
e-mail: anh@dtu.dk

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Power supply on chip (PwrSoC) is the vision of miniaturized switched-mode power supplies with a monolithic integration of all active and passive components [1], [2]. Passive inductors are by far the most bulky and expensive parts in power supplies. Increasing operating frequency to very high frequency (VHF: 30 – 300 MHz) allows the usage of smaller inductors thus reducing the size of power supplies. Indeed, with the inductance of tens of nH [3], integrated air-core inductors are suitable for VHF power converters.

Last year we reported on the fabrication of a 3D MEMS air-core toroidal inductor. In the present work, we demonstrate its application in a power converter. The inductors are electrically characterized with small signal measurement, and tested in a VHF class E resonant boost converter.

Briefly, the MEMS inductor is designed with a silicon-embedded 3D construction consisting of through-Si vias (TSVs) arranged in a toroidal shape, suspended copper (Cu) windings, and Si fixtures [4]. The inductors are fabricated with a four-step 3D fabrication process (Fig. 1). These are (i) through-wafer deep reactive ion etching of TSVs, (ii) electroplating Cu TSVs and top and bottom Cu layers, (iii) spray coating of resist and wet etching, and (iv) removing Si core by isotropic ICP etching. The MEMS inductor is shown in Fig. 2a. The suspended windings are attached to the Si support die by five fixtures.

Air-core and Si-core inductors are electrically characterized and compared using an impedance analyzer (Agilent 4294a). The frequency is between 1 to 110 MHz. The tested inductors have 20 turns, 1.5 mm outer radius, 0.75 mm inner radius, and 350 μ m height. The inductances are 44.6 nH and 43.9 nH for the air-core and Si-core inductor, respectively. Air-core inductors have superior performance with higher quality factor (Q) of 13.3 at 33 MHz compared to Q of 9 at 20 MHz of Si-core inductors. With the complete removal of the Si core, the parasitic capacitance reduces three folds from 11.5 pF to 3.7 pF, thus allowing a higher Q at higher frequencies. A higher Q indicates that air-core inductors have lower power losses than Si-core inductors, and therefore achieve a higher power conversion efficiency.

To demonstrate the application of our fabricated inductor, a VHF Class E resonant converter is designed, simulated with LT-SPICE, and implemented using our MEMS inductor (L_2) and a high-performance gallium nitride field-effect transistor as key components. The converter consists of a class E resonant inverter and a current-driven rectifier (Fig. 2b). The MEMS inductor is used as part of the resonant network in the inverter. It is glued onto the PCB by epoxy and the electrical connections are made by three gold wire bonds. The detailed working principle of the converter can be found in [5]. In brief, the converter is designed to operate at 33 MHz in zero voltage switching (ZVS) mode to reduce switching losses. The converter achieved an efficiency of 77% converting 8.4 V_{DC} to 12.4 V_{DC} and delivered 7.72 W to the load with a total loss of 2.32 W (Fig. 3). The simulated AC current in the MEMS inductor is 1 A RMS. The AC power loss in L_2 is estimated via DC power loss using thermal measurement method. An increasing DC current is driven through L_2 until the thermal images are match (Fig. 4). An AC power loss of 0.98 W is obtained.

At the MNE conference, we look forward to present in detail the applications of our air-core inductors in power supplies.

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Power Converters,” in review.

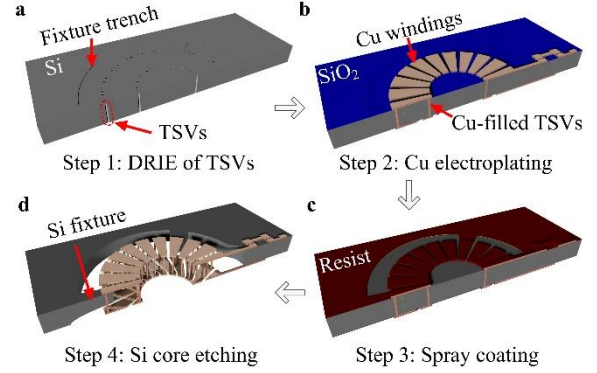


Figure 1 (a) Four-step fabrication process (direction A-A' in Fig. 2a).

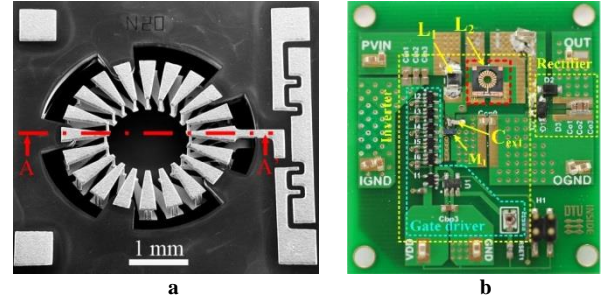


Figure 2 (a) A SEM image of the fabricated MEMS air-core toroidal inductor. (b) Class E resonant boost converter with two parts: inverter and rectifier. The inductor (L_2) is connected to the PCB via gold bond wires.

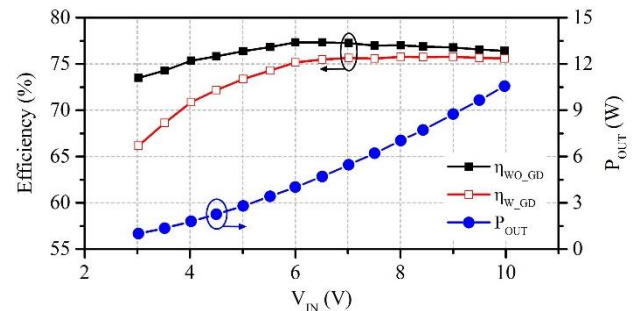


Figure 3 Efficiency with gate driver loss (η_{W_GD}), efficiency without gate driver loss (η_{WO_GD}), and output power (P_{OUT}) are measured with an input voltage sweep from 3 V_{DC} to 10 V_{DC}. The converter operates in zero voltage switching (ZVS) mode at 33 MHz and achieves an efficiency of 77% at V_{IN} = 8.4 V with an output power of 7.72 W.

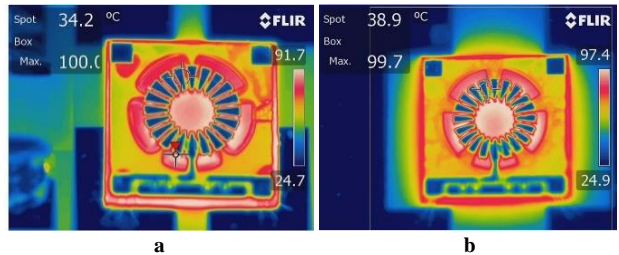


Figure 4 Thermal performance of the fabricated air-core inductor in (a) an operating class E resonant boost converter which converts 8.4 V_{DC} to 12.4 V_{DC}, (b) a PCB test board with DC power loss. AC Power loss is estimated via DC power loss with temperature matching. The temperatures are matched at a 1.53 A DC current and 0.646 V DC voltage. AC power loss equals to DC power loss is 0.98 W